

Quark mass dependence of the ground-state octet baryons in next-to-next-to-next-to-leading order covariant baryon chiral perturbation theory

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Abstract We report on a recent study of the ground-state octet baryon masses using the covariant baryon chiral perturbation theory with the extended-on-mass-shell renormalization scheme up to next-to-next-to-next-to-leading order. By adjusting the available 19 low-energy constants, a good fit of the $n_f = 2 + 1$ lattice quantum chromodynamics results from the PACS-CS, LHPC, HSC, QCDSF-UKQCD and NPLQCD collaborations is achieved.

Keywords Chiral Lagrangians · Lattice QCD simulations · Baryon masses

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1 Introduction

Recently, the lowest-lying baryon spectrum, composed of up, down and strange quarks, has been studied by various lattice quantum chromodynamics (LQCD) collaborations [1–9]. At present, most of the LQCD simulations are still performed in a finite hypercube and with larger than physical light quarks masses [10], the final results can only be obtained by extrapolating to the physical point (chiral extrapolation) and infinite space-time (finite-volume corrections). Baryon chiral perturbation theory (BChPT) provides a useful framework to perform such extrapolations and to study the induced uncertainties.

In the past decades, the ground-state (g.s.) octet baryon masses have been studied extensively in BChPT [11–26]. However, up to now, a simultaneous description of all the $n_f = 2 + 1$ LQCD data with finite-volume effects taken into account self-consistently is still missing. Such a study is necessary for a clarification of the convergence problem and for testing the consistency between different LQCD simulations [27]. Furthermore, it helps determine/constrain the many unknown LECs of BChPT at next-to-next-to-next-to-leading order (N^3LO).

In this work we study the g.s. octet baryon masses using the EOMS-BChPT up to N^3LO . Finite-volume corrections to the lattice data are calculated self-consistently [28] and are found to be important in order to obtain a good fit of the LQCD data. Unlike Refs. [21, 24], the virtual decuplet contributions are not explicitly included, because its effects can not be disentangled from those of virtual octet baryons due to the large number of unknown LECs. In order to fix all the 19 LECs and test the consistency of current LQCD calculations, we perform a simultaneous fit of all the publicly available $n_f = 2 + 1$ LQCD data from the PACS-CS [3], LHPC [5], HSC [6], QCDSF-UKQCD [8] and NPLQCD [9] collaborations.

2 Results and discussion

The details of the calculation can be found in Ref. [29]. Here we only briefly summarize the main results. Up to N^3LO , there are 19 LECs to be determined. To make sure that N^3LO BChPT is suitable for the description of the LQCD data, we have chosen two groups of LQCD data according to the following two criteria. For the first group, we require $M_\pi^2 < 0.25 \text{ GeV}^2$ and $M_\phi L > 4$ with $\phi = \pi, K, \eta$ and L the spacial dimension of the LQCD simulation. For the second, we require $M_\pi^2 < 0.5 \text{ GeV}^2$, $M_K^2 < 0.7 \text{ GeV}^2$ and $M_\phi L > 3$. In the following, we refer to these two groups of LQCD data as data Set-I and Set-II.

We perform a χ^2 fit to the LQCD data and the physical octet baryon masses by varying the 19 LECs. The so-obtained values of the LECs from the best fits are listed in Table 6 of Ref. [29]. For the sake of comparison, we have fitted Set-I using the NLO and NNLO EOMS-BChPT. The values of the LECs b_0 , b_D , b_F , and m_0 are also tabulated in Table 6 of Ref. [29]. An order-by-order improvement is clearly seen, with decreasing $\chi^2/\text{d.o.f.}$ at each increasing chiral order. Apparently, only using the $\mathcal{O}(q^3)$ chiral expansion, one cannot describe simultaneously the LQCD data from the five collaborations. The corresponding $\chi^2/\text{d.o.f.}$ is about 8.6. On the other hand, in the N^3LO fit of lattice data Set-I and experimental octet baryon masses, $\chi^2/\text{d.o.f.} = 1.0$. In addition, the values of the fitted LECs (named Fit I)

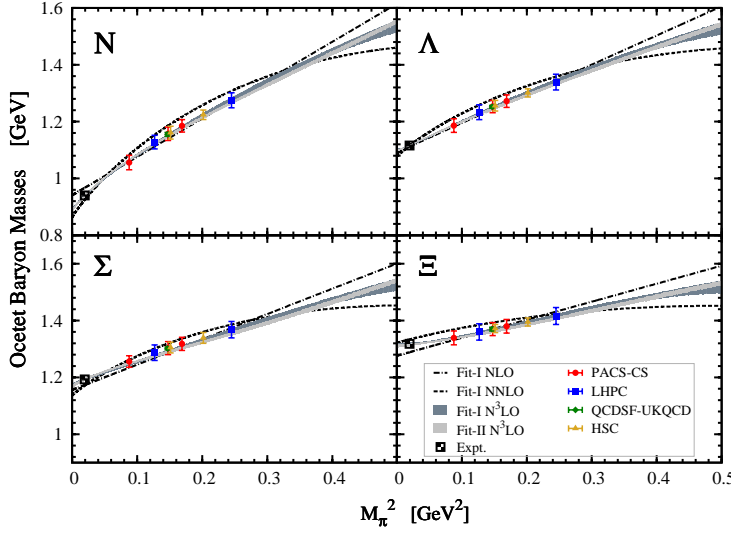


Fig. 1 (Color online). The lowest-lying baryon octet masses as functions of the pion mass squared. The two bands correspond to the best $\mathcal{O}(q^4)$ fit to lattice data Set-I and Set-II, and the dot-dashed lines and dashed lines are the best NLO and NNLO fits to lattice data Set-I. In obtaining the ChPT results, the strangeness quark mass has been set to its physical value. The lattice numbers are projected ones with $N^3\text{LO}$ BChPT with the LECs determined from the best fit to Set-I and their strange quark mass is also set to the physical value. (Taken from Ref. [29].)

all look very natural. Especially, the baryon mass in the chiral limit $m_0 = 880$ MeV seems to be consistent with the $SU(2)$ -BChPT value [30, 31]. The fit to data Set-II yields a $\chi^2/\text{d.o.f.}$ about 1.6 and the fitted LECs look similar to those from Fit I except b_2 , b_6 , b_7 and b_8 . The increased $\chi^2/\text{d.o.f.}$ indicates that data Set-II is a bit beyond the region of applicability of $N^3\text{LO}$ BChPT.

In Fig. 1, setting the strange-quark mass to its physical value, we plot the light-quark mass evolution of N , Λ , Σ and Ξ as functions of M_π^2 using the LECs from Table 6 of Ref. [29]. We can see that the NNLO fitting results are more curved and do not describe well lattice data Set-I. On the contrary the two $N^3\text{LO}$ fits, named Fit I and Fit II, both can give a good description of lattice data Set I. The rather linear dependence of the lattice data on M_π^2 at large light quark masses, which are exhibited both by the lattice data [5] and reported by other groups, is clearly seen.

3 Summary and Conclusions

We have studied the lowest-lying octet baryon masses with the EOMS BChPT up to $N^3\text{LO}$. The unknown LECs are determined by a simultaneous fit of the latest $n_f = 2 + 1$ LQCD simulations from the PACS-CS, LHPC, HSC, QCDSF-UKQCD and NPLQCD collaborations. Finite-volume corrections are calculated self-consistently. It is shown that the eleven lattice data sets with $M_\pi^2 < 0.25$

GeV^2 and $M_\phi L > 4$ ($\phi = \pi, K, \eta$) can be fitted with a $\chi^2/\text{d.o.f.} = 1.0$. Including more lattice data with larger pion masses or smaller volumes deteriorates the fit a bit but still yields a reasonable $\chi^2/\text{d.o.f.} = 1.6$.

Our studies confirm that covariant BChPT in the three flavor sector converges as expected, i.e., relatively slowly as dictated by $m_K/\Lambda_{\chi\text{SB}}$ but with clear improvement order by order, at least concerning the octet baryon masses. A successful simultaneous fit of all the latest $n_f = 2 + 1$ LQCD simulations indicates that the LQCD results are consistent with each other, though their setups are quite different.

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